

# Tailoring Chirp in Spin-Lasers

Guilhem Boeris<sup>1,2</sup>, Jeongsu Lee<sup>1</sup>, Karel Výborný<sup>1,3</sup>, and Igor Žutić<sup>1\*</sup>

<sup>1</sup> *Department of Physics, State University of New York at Buffalo, NY 14260, USA*

<sup>2</sup> *Département de Physique, Ecole Polytechnique, 91128 Palaiseau Cedex, France*

<sup>3</sup> *Institute of Physics ASCR, v.v.i., Cukrovarnická 10, CZ-16253, Praha 6, Czech Republic*

(Dated: February 22, 2012)

The usefulness of semiconductor lasers is often limited by the undesired frequency modulation, or chirp, a direct consequence of the intensity modulation and carrier dependence of the refractive index in the gain medium. In spin-lasers, realized by injecting, optically or electrically, spin-polarized carriers, we elucidate paths to tailoring chirp. We provide a generalized expression for chirp in spin-lasers and introduce modulation schemes that could simultaneously eliminate chirp and enhance the bandwidth, as compared to the conventional (spin-unpolarized) lasers.

Many advantages of lasers stem from their modulation response, in which refractive index and optical gain depend on carrier density  $n$ .<sup>1,2</sup> Modulation  $\delta n(t)$  thus generates both the intensity (photon density)  $\delta S(t)$  and frequency modulation  $\delta \nu(t)$  of the emitted light. Such  $\nu(t)$ , known as chirp,<sup>1</sup> is usually a parasitic effect associated with linewidth broadening, enhanced dispersion, and limiting the high bit-rate in telecommunication systems.<sup>3</sup> Various approaches have therefore focused on low-chirp modulation: pulse shaping,<sup>3</sup> injection locking,<sup>4</sup> temperature modulation,<sup>5</sup> and employing quantum dots as the gain region.<sup>6</sup> In conventional lasers for small signal analysis<sup>6</sup> (SSA) in which the quantities of interest are decomposed into a steady state and modulated part  $X = X_0 + \delta X(t)$ , the chirp is given by<sup>1</sup>

$$\delta \nu(t) = [\Gamma g_0 / (4\pi)] \alpha_0 \delta n(t), \quad (1)$$

where  $\Gamma$  is the optical confinement factor,  $g_0$  the gain coefficient, and  $\alpha_0 = (\partial \hat{n}_r / \partial n) / (\partial \hat{n}_i / \partial n)$  is the linewidth enhancement factor,<sup>6</sup> expressed in terms of complex refraction index  $\hat{n} = \hat{n}_r + i\hat{n}_i$  in the active region.

In the emerging class of semiconductor lasers, known as spin-lasers,<sup>7-23</sup> with total injection  $J = J_+ - J_-$  containing inequivalent spin up/down contributions ( $J_+$ ,  $J_-$ ), we expect additional possibilities for tailoring chirp.  $J_+ \neq J_-$  is realized using circularly-polarized photoexcitation or electrical injection from a magnetic contact. The polarization of emitted light resolved in two helicities,  $S = S^+ + S^-$ , can be understood from the optical selection rules.<sup>24</sup> For example, in the quantum well-based spin-lasers with  $J$  close to the lasing threshold, recombination of spin-up (spin-down) electrons and heavy holes yields  $S^-$  ( $S^+$ ) polarized light. Both amplitude modulation (AM)  $\delta J(t)$  [see Fig. 1(a)] and polarization modulation (PM)  $\delta P_J(t)$ , of injection polarization<sup>24</sup>  $P_J = (J_+ - J_-) / (J_+ + J_-)$ , can be readily implemented. With PM the emitted light could be modulated even at a fixed  $J$  and  $n$ .<sup>16</sup> While Eq. (1) then suggests a chirp-free operation, we show that such a simple reasoning is not always true and suitable generalization for chirp in spin-lasers is required.

Our generalized picture reveals that AM and PM in spin-lasers enable both reduced chirp and enhanced

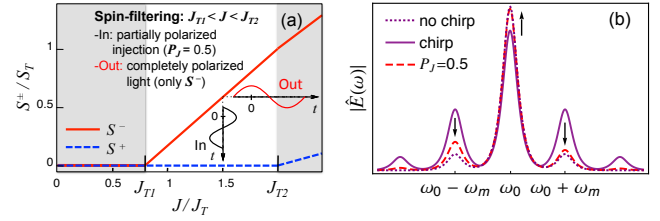


FIG. 1: (Color online) (a) Helicity-resolved photon density ( $S^\pm$ ) as a function of injection ( $J$ ), normalized to  $S_T = S(2J_T)$  and unpolarized injection threshold  $J_T$ , respectively. For spin-polarized injection,  $|P_J| > 0$ , there are two thresholds<sup>16</sup>  $J_{T1,2}$  for  $S^\mp$ . AM (harmonic curves) for  $J \in (J_{T1}, J_{T2})$  yields modulation of fully polarized light (spin-filtering, unshaded area). (b) Broadened electric field spectrum for AM. Conventional lasers ( $P_J = 0$ ) without (dotted line) and with chirp (solid), and spin-laser with  $P_J = 0.5$  (dashed) are shown. Arrows indicate the chirp reduction by spin injection. Modulation amplitudes for  $P_J = 0.5$  and  $P_J = 0$  are chosen to provide the same spectra for no chirp. The choice of colors reflects that an unpolarized  $S$  is an equal weight superposition of  $S^+$  and  $S^-$ , while for  $P_J = 0.5$  the emitted light is  $S^-$ .

modulation bandwidth, as compared to their spin-unpolarized ( $P_J = 0$ ) counterparts. PM could also provide an efficient spin communication.<sup>25</sup>

The chirp can be simply quantified by comparing the ratio of the central and first sideband peaks in the emitted light.<sup>26</sup> To visualize this effect, in Fig. 1(b) we show the spectrum of electric field which can be written as<sup>2</sup>

$$E(t) \simeq E_0 [1 + \delta S(t) / (2S_0)] \text{Re}\{e^{i[2\pi\nu_0 t + \phi(t)]}\}, \quad (2)$$

where  $E_0$  is a real amplitude of the field, the phase is  $\phi(t) = 2\pi \int_0^t \delta \nu(t') dt'$ , and  $\nu_0$  ( $\omega_0$ ) is (angular) frequency of the output light. Using rate equations (REs) we calculate harmonic modulation with  $\omega_m$  in SSA<sup>27</sup> and obtain  $\phi(t) = [|\delta \nu(\omega_m)| / \nu_m] \sin(\omega_m t + \phi_\nu)$ , where  $\phi_\nu = \arg[\delta \nu(\omega_m)]$ . The undesirable alteration to the original spectrum caused by chirp can be quantified by the ratio between the heights of the first sidebands with and without chirp. For spin-unpolarized lasers, an identity<sup>2</sup>  $e^{i\delta \sin x} = \sum_{n=-\infty}^{\infty} J_n(\delta) e^{inx}$ , with asymptotic approxi-

mation  $\delta \ll 1$  for Bessel functions  $J_n(\delta)$ , leads to<sup>1,3</sup>

$$\frac{\text{sideband height with chirp}}{\text{sideband height without chirp}} \simeq \sqrt{1 + 4 \left( \frac{\text{FM}}{\text{IM}} \right)^2}, \quad (3)$$

where the ratio of frequency and intensity modulation index FM/IM can be expressed as<sup>1,3</sup>

$$\text{FM/IM} = [\delta\nu(\omega_m)/\nu_m]/[\delta S(\omega_m)/S_0]. \quad (4)$$

Equation (3) accurately gives the variation of the first sidebands in Fig. 1(b). The phase induced by the chirp also creates higher order sidebands further away. However, by the spin-polarized injection modulation, chirp and thus alteration of the spectrum can be suppressed.

To define chirp in spin-lasers, we recall that the generalization of the usual model of optical gain term<sup>12,16</sup> is  $g_0(n - n_{\text{tran}}) \rightarrow g_0(n_{\pm} + p_{\pm} - n_{\text{tran}}) = g_0[(3/2)n_{\pm} + (1/2)n_{\mp} - n_{\text{tran}}]$ , where  $g_0$  is density-independent coefficient,  $n_{\text{tran}}$  the transparency density, and  $n_{\pm}$  ( $p_{\pm}$ ) are electron (hole) spin-resolved density. Here 3:1 ratio of  $n_{\pm}$  contributions follows from the charge neutrality and the very fast spin relaxation of holes<sup>12</sup>  $p_{\pm} = n/2$  and this ratio reflects also the gain anisotropy for  $S^+$  and  $S^-$ .

For spin-lasers the generalization of Eq. (1) is then

$$\delta\nu(t) = \frac{\Gamma g_0}{4\pi} \left[ \frac{3}{2}\alpha_+\delta n_+(t) + \frac{1}{2}\alpha_-\delta n_-(t) \right], \quad (5)$$

where we focus on the spin-filtering regime [Fig. 1(a)],  $J \in (J_{T1}, J_{T2})$ , and  $\alpha_{\pm} = (\partial\hat{n}_r/\partial n_{\pm})/(\partial\hat{n}_i/\partial n_{\pm})$ .<sup>28</sup> For  $P_J > 0$  the spin filtering implies  $S^-$  emitted light.<sup>29</sup> When  $P_J = 0$  (thus  $n_+ = n_-$ ), Eq. (5) reduces to Eq. (1) since

$$\alpha_0 = (3\alpha_+ + \alpha_-)/4. \quad (6)$$

While for  $P_J \neq 0$ , Eq. (6) is not always true (since  $\alpha_{\pm}$  depends on  $n_{\pm}$ ), we still use it to relate  $\alpha_{\pm}$  and  $\alpha_0$ . This approximation is precise for  $J$  slightly below  $J_{T2} = J_T/(1 - P_{J0})$  where  $n_+ - n_- \rightarrow 0$ .

With typical spin-lasers, realized as vertical cavity surface emitting lasers,<sup>8–11,15,17</sup> in the spin-filtering regime it is accurate to use<sup>12</sup> vanishing gain compression and spontaneous emission factors ( $\epsilon = \beta = 0$ ).<sup>30</sup> With a generalized chirp formulation [Eq. (5)], we employ REs<sup>16</sup> and SSA to obtain the results from Fig. 1(b). We confirm the chirp suppression in spin-lasers with the spectrum approaching the chirp-free case.

In conventional lasers, the chirp reduction is particularly important for high-frequency modulation where the transient chirp [ $\propto d \ln S(t)/dt$ , only weakly  $\epsilon$ -dependent] is the dominant contribution.<sup>1–3</sup> FM/IM is a constant

$$\frac{\delta\nu(\omega_m)/\nu_m}{\delta S(\omega_m)/S_0} = -i \frac{\alpha_0}{2}, \quad (7)$$

which provides both a suitable way to experimentally extract<sup>1</sup> the linewidth enhancement factor  $\alpha_0$ , and a

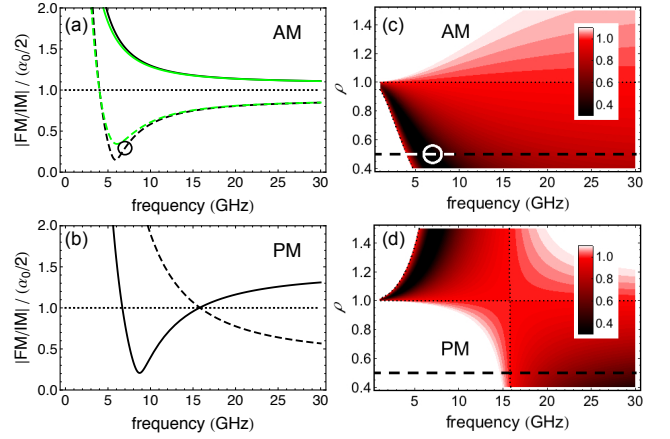


FIG. 2: (Color online)  $|\text{FM/IM}|$  normalized to the conventional value  $\alpha_0/2$  for (a) AM and (b) PM, shown for  $\rho \equiv \alpha_+/\alpha_- = 2$  (solid) and  $\rho = 0.5$  (dashed). Green (gray) curves reveal only a small change for finite electron spin relaxation time,<sup>27</sup>  $\tau_s = \tau_r$ . The regime of reduced chirp in spin-lasers (darker regions) is delimited with dotted lines for (c) AM and (d) PM. The circle in (a) and (c) for  $\rho = 0.5$  represents the sampling point to generate Fig. 1(b).  $J_0 = 1.9J_T$  and  $P_{J0} = 0.5$  are used in (a)-(d).

simple comparison for chirp in spin-lasers. In the spin-filtering regime  $|\text{FM/IM}|$  depends on the modulation frequency  $\omega_m$  and the ratio  $\rho \equiv \alpha_+/\alpha_-$  [see Eq. (5)]

$$\left| \frac{\delta\nu/\nu_m}{\delta S/S_0} \right| / \frac{\alpha_0}{2} = \frac{3\rho\delta n_+(\omega_m) + \delta n_-(\omega_m)}{3\delta n_+(\omega_m) + \delta n_-(\omega_m)} \left( \frac{4}{1 + 3\rho} \right). \quad (8)$$

$|\text{FM/IM}|$  of spin lasers is shown in Fig. 2. A choice of  $\rho \in [0.5, 2]$  is motivated by our preliminary microscopic calculation (Kubo formalism) of  $\alpha_+$  and  $\alpha_-$  for GaAs. The normalized ratio  $|\text{FM/IM}| < 1$  represents the chirp reduction relative to conventional lasers. For AM a change  $\rho = 2 \rightarrow 0.5$  leads to a smaller chirp for all range of modulation frequencies in Fig. 2(a). Black and gray (green) curves show only a small change in the results for electron spin relaxation time  $\tau_s$ , being infinite and equal to the recombination time  $\tau_r$ , respectively. Since in spin-lasers at 300 K  $\tau_s/\tau_r \sim 10$ ,<sup>15</sup> it is accurate to choose  $\tau_s \rightarrow \infty$  in REs for the rest of our analysis.

For PM in Fig. 2(b) the same change  $\rho = 2 \rightarrow 0.5$  yields a non-monotonic effect on the chirp reduction which, compared to the conventional lasers, is realized at  $\nu_m \lesssim 16$  GHz ( $\rho = 2$ ) and at  $\nu_m \gtrsim 16$  GHz ( $\rho = 0.5$ ), respectively. These trends for AM and PM are further shown in Figs. 2(c) and (d) for a range of  $\rho$ , where the region of the favorable  $|\text{FM/IM}|$  reduction is delimited with dotted lines. Consistent with Eq. (8),  $|\text{FM/IM}|$  at  $\rho = 1$  yields the conventional value  $\alpha_0/2$ , for both AM and PM. Since such a conventional value is retained even for PM and  $\delta n(t) = 0$ , there is a striking difference between the usual chirp in Eq. (1), and that for spin-lasers in Eq. (5).

Our discussion of FM/IM shows that the chirp is not

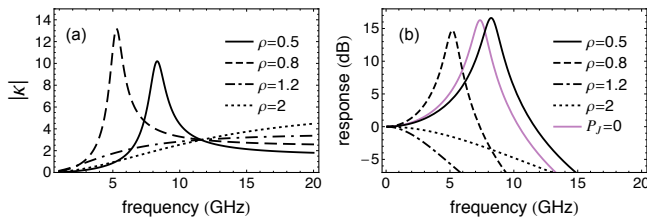


FIG. 3: (Color online) SSA of CM. (a) Chirp-tailoring function  $\kappa(\nu_m)$  and (b) modulation response  $|R(\nu_m)/R(0)|^2$  are shown for  $J_0 = 1.2 J_T$ ,  $P_{J0} = 0.5$  and different  $\rho$ 's. The response of conventional laser (AM,  $P_J = 0$ ) is given (gray/purple) for comparison.

completely removed using PM or AM. However, it is possible to achieve zero-chirp by introducing a scheme we term complex modulation (CM): one of the spin-resolved injections ( $J_+$  for  $P_{J0} > 0$ ) is the input signal, while the other is used only to cancel the chirp. From Eq. (8), the zero-chirp condition is  $\delta n_-(\omega_m)/\delta n_+(\omega_m) = -3\alpha_+/\alpha_- = -3\rho$ , which can be satisfied by introducing a chirp-tailoring function  $\kappa(\omega_m)$  obtained from SSA

$$\delta J_-(\omega_m) = \kappa(\omega_m) \delta J_+(\omega_m). \quad (9)$$

Here  $\delta J_+$  is the input modulation responsible for the modulation of emitted light  $\delta S^-$ , while the correction current  $\delta J_-$  compensates the variation of the carrier density to reduce the chirp.

We next use SSA to consider the implications of CM on the modulation bandwidth, shown together with the chirp-tailoring function  $\kappa$  in Fig. 3. The CM relaxation oscillation frequency, represented by the peak positions in Figs. 3(a) and (b) for  $\rho \leq 1$ , can be expressed as

$$\omega_R^{CM} \simeq \{\Gamma g_0 J_T (J/J_{T1} - 1)(1 - \rho)\}^{1/2}, \quad (10)$$

where  $J_{T1} = J_T/(1 + P_{J0}/2)$  is the reduced threshold in a spin-laser.<sup>12</sup> The peak positions coincide for  $|\kappa(\omega_m)|$

and for the modulation response function<sup>16</sup>  $R(\omega_m) = |\delta S^-(\omega_m)/\delta J_+(\omega_m)|$  because the character of  $J_-(\omega_m) \propto \kappa(\omega_m)$  propagates through  $n_\pm$  and  $S^-$  into  $R(\omega_m)$ . For  $\rho > 1$ ,  $|\kappa(\omega_m)|$  increases monotonically with  $\omega_m$  showing no peak. Zero-chirp is not feasible for  $\rho = 1$  since it is the same FM/IM as in conventional lasers [Eq. (8)].

By comparing  $\omega_R^{CM}$  in Eq. (10) for  $\rho \leq 1$  to  $\omega_R^{AM}$  and  $\omega_R^{PM}$  from Ref. 16:  $\omega_R^{AM,PM} \simeq \{\Gamma g_0 J_T (J/J_{T1} - 1)\}^{1/2}$ , we see that CM has narrower bandwidth than AM and PM (estimated by  $\omega_R$ ), for the same  $P_{J0}$ . While CM provides a path for removing chirp, it may come at the cost of a reduced bandwidth. However, an optimized value of  $\rho = 0.5$  in Fig. 3(b) yields simultaneously zero chirp and bandwidth enhancement, as compared to conventional lasers.

What about experimental feasibility to control chirp in spin-lasers? While CM has yet to be attempted, it can be viewed as a combination of AM and PM which individually already lead to an improved chirp (Figs. 1 and 2) and have been demonstrated in spin-lasers. Slow PM has been realized<sup>8</sup> using a Soleil-Babinet polarization retarder at a fixed  $J \in (J_{T1}, J_{T2})$ . Fast PM ( $\nu_m \sim 40$  GHz) can be implemented with a coherent electron spin precession in a transverse magnetic field,<sup>7</sup> or a mode conversion in an electro-optic modulator.<sup>31</sup> Recent advances in using birefringence for PM<sup>32</sup> suggest that chirp reduction in spin-lasers could be feasible at higher injection, beyond the spin-filtering regime we have considered.

To further enhance the opportunities in spin-lasers, it would be helpful to utilize other gain media and achieve technologically important emission at 1.3 and 1.55  $\mu\text{m}$ . We expect that our proposals will stimulate additional work towards understanding the spin-dependence of refractive index (already used for fast all-optical switching<sup>33</sup>) and its implications for spin-lasers.

We thank H. Dery, R. Oszwałdowski, A. Petrou, and N. Tesařová for discussions. This work was supported by the NSF-ECCS, AFOSR-DCT, U.S. ONR, NSF-NRI NEB 2020, and SRC.

\* Electronic address: zigor@buffalo.edu

<sup>1</sup> L. A. Coldren and S. W. Corzine, *Diode Lasers and Photonic Integrated Circuits*, (Wiley, New York, 1995).

<sup>2</sup> A. Yariv, *Optical Electronics in Modern Communications*, 5<sup>th</sup> Edition (Oxford University, New York, 1997).

<sup>3</sup> K. Petermann *Laser Diode Modulation and Noise*, (Kluwer Academic, Dordrecht, 1988).

<sup>4</sup> G. H. M. van Tartwijk and G. P. Agrawal, *Prog. Quantum Electron.* **22**, 43 (1998).

<sup>5</sup> V. B. Gorfinkel and S. Luryi, *Appl. Phys. Lett.* **62**, 2923 (1993).

<sup>6</sup> S. L. Chuang, *Physics of Optoelectronic Devices*, 2nd ed. (Wiley, New York, 2009).

<sup>7</sup> S. Hallstein, J. D. Berger, M. Hilpert, H. C. Schneider, W. W. Rühle, F. Jahnke, S. W. Koch, H. M. Gibbs, G. Khitrova, and M. Oestreich, *Phys. Rev. B* **56**, R7076

(1997).

<sup>8</sup> J. Rudolph, D. Hägele, H. M. Gibbs, G. Khitrova, and M. Oestreich, *Appl. Phys. Lett.* **82**, 4516 (2003).

<sup>9</sup> J. Rudolph, S. Döhrmann, D. Hägele, M. Oestreich, and W. Stolz *Appl. Phys. Lett.* **87**, 241117 (2005).

<sup>10</sup> M. Holub, J. Shin, D. Saha, and P. Bhattacharya, *Phys. Rev. Lett.* **98**, 146603 (2007).

<sup>11</sup> S. Hövel, A. Bischoff, N. C. Gerhardt, M. R. Hofmann, T. Ackemann, A. Kroner, and R. Michalzik, *Appl. Phys. Lett.* **92**, 041118 (2008).

<sup>12</sup> C. Götthgen, R. Oszwałdowski, A. Petrou, and I. Žutić, *Appl. Phys. Lett.* **93**, 042513 (2008).

<sup>13</sup> I. Vurgaftman, M. Holub, B. T. Jonker, and J. R. Mayer, *Appl. Phys. Lett.* **93**, 031102 (2008).

<sup>14</sup> D. Basu, D. Saha, C. C. Wu, M. Holub, Z. Mi, and P. Bhattacharya, *Appl. Phys. Lett.* **92**, 091119 (2008).

- <sup>15</sup> H. Fujino, S. Koh, S. Iba, T. Fujimoto, and H. Kawaguchi, Appl. Phys. Lett. **94**, 131108 (2009).
- <sup>16</sup> J. Lee, W. Falls, R. Oszwaldowski, and I. Žutić, Appl. Phys. Lett. **97**, 041116 (2010).
- <sup>17</sup> D. Saha, D. Basu, and P. Bhattacharya, Phys. Rev. B **82**, 205309 (2010).
- <sup>18</sup> I. Žutić, R. Oszwaldowski, J. Lee, and C. Gøthgen in *Handbook of Spin Transport and Magnetism*, edited by E. Y. Tsybal and I. Žutić (CRC Press, New York, 2011).
- <sup>19</sup> S. Iba, S. Koh, K. Ikeda, and H. Kawaguchi, Appl. Phys. Lett. **98**, 08113 (2011).
- <sup>20</sup> R. Al-Seyab, D. Alexandropoulos, I. D. Henning, and M. H. Adams, IEEE Photon. J. **3**, 799 (2011); M. San Miguel, Q. Feng, and J. V. Moloney, Phys. Rev. A **52**, 1728 (1995).
- <sup>21</sup> M. Holub and B. T. Jonker, Phys. Rev. B **83**, 125309 (2011).
- <sup>22</sup> D. Banerjee, R. Adari, M. Murthy, P. Suggisetti, S. Ganguly, and D. Saha, J. Appl. Phys. **109**, 07C317 (2011).
- <sup>23</sup> J. Lee, R. Oszwaldowski, C. Gøthgen, and I. Žutić, Phys. Rev. B **85**, 045314 (2012).
- <sup>24</sup> I. Žutić, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. **76**, 323 (2004); J. Fabian, A. Matos-Abiad, C. Ertler, P. Stano, and I. Žutić, Acta Phys. Slov. **57**, 565 (2007).
- <sup>25</sup> H. Dery, Y. Song, P. Li, and I. Žutić, Appl. Phys. Lett. **99**, 082502 (2011).
- <sup>26</sup> Y. Arakawa and A. Yariv, Appl. Phys. Lett. **47**, 905 (1985).
- <sup>27</sup> We base SSA on the rate equations Eqs. (4)-(6) for conventional lasers and Eqs. (22) and (A1) for spin lasers in Ref. 23. The parameters used for numerical calculations are given in Table I from Ref. 16.
- <sup>28</sup> We can infer that  $\alpha_+ \neq \alpha_-$ , since the Faraday angle, representing the asymmetry of the refractive indices for  $S^\pm$ , depends on  $n$  [S. Crooker, D. Awschalom, J. Baumberg, F. Flack, and N. Samarth, Phys. Rev. B **56**, 7574 (1997); R. Bratschitsch, Z. Chen, and S. T. Cundiff, Phys. Stat. Sol. (c) **0**, 1506 (2003)].
- <sup>29</sup> If there is an emitted light with the other helicity, the chirp from  $S^+$  signal,  $\delta\nu'(t)$ , can be written analogously:  $\delta\nu'(t) = \Gamma g_0 / (4\pi) [(1/2)\alpha'_+ \delta n_+(t) + (3/2)\alpha'_- \delta n_-(t)]$ .
- <sup>30</sup> Our approximation  $\beta = 0$  throughout the paper, used also in Fig. 1, accurately captures the expected behavior for experiments on spin-lasers at 300 K, parametrized with  $\beta \sim 10^{-5}$  in Ref. 9.
- <sup>31</sup> J. D. Bull, N. A. F. Jaeger, H. Kato, M. Fairburn, A. Reid, and P. Ghanipour, Photonics North 2004: Optical Components and Devices, Ottawa, Canada, [J. C. Armitage, S. Fafard, R. A. Lessard, and G. A. Lampropoulos, Proc. SPIE **5577**, 133 (2004)].
- <sup>32</sup> N. C. Gerhardt, M. Y. Li, H. Jähme, H. Höpfner, T. Ackemann, and M. R. Hofmann, Appl. Phys. Lett. **99**, 151107 (2011).
- <sup>33</sup> Y. Nishikawa, A. Tackeuchi, S. Nakamura, S. Muto, and N. Yokoyama Appl. Phys. Lett. **66**, 839 (1995).